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WIDESPREAD OCCURRENCE OF FAYALITE IN CERTAIN IGNEOUS ROCKS OF CENTRAL WISCONSIN.

IN central Wisconsin, in the vicinity of Wausau, forming the southern portion of the pre-Cambrian district of the northern half of the state, is a wide variety of intrusive igneous rocks. Chief among these intrusives, which constitute perhaps 75 per cent. of the rock formations for many miles around Wausau, is a complex series of holocrystalline rocks ranging from granite, high in silica, to quartz syenite, nepheline, and sodalite syenites, and related basic, alkali-rich rocks. Associated with this series are an older series of basic rocks and a still older flow of rhyolite, to both of which the various members of the granite-syenite series bear the same structural relations.

The habitat of the fayalite is in certain phases of the granite-syenite series, and it is not known to be in the other varieties of igneous rock of the region. The mineral fayalite, it will be recalled, is the pure iron olivine, iron chrysolite, having the formula $2FeO, SiO_2$, and the theoretical composition, ferrous oxide 70.6, and silica 29.4 per cent. Considered in its entirety, the series in which the fayalite occurs resembles in many respects, though not in all, other well-known series of nepheline-bearing and related alkali-rich rocks, such as those in Arkansas, in the Christiania region of southern Norway, and in Essex County, Mass.

The composition of some of the phases of the central Wisconsin alkali-rich rocks is shown in the subjoined table. The analyses were made by Professor W. W. Daniells, professor of chemistry in the University of Wisconsin.

In the analyses attention is called to the fairly regular increase in amount of alumina and the alkalies as the silica decreases. The iron is abundant and is fairly uniform in amount, with the exception of that in the granite rich in quartz. With respect to the lime and magnesia, these constituents, like the iron, do not differ appreciably in the various phases. Attention is especially called to the uniformly low content of magnesia, which is without doubt one of the causes of the development of the ferrous silicate, fayalite, in the magma.

	I	II	III	IV	V	VI
SiO_2	76.54	67.99	61.18	57.48	54.79	54.76
Al_2O_3	13.82	15.85	19.72	20.04	22.87	24.72
Fe_2O_3	1.62	5.36	3.71	5.64	1.74	2.73
FeO	....		1.32	3.76	3.24	2.35
MnO	....	....	....	....	trace	....
MgO	0.01	0.41	trace	0.40	1.92	0.10
CaO	0.85	1.78	2.64	1.70	trace	1.67
Na_2O	4.32	3.21	5.28	7.25	10.75	10.38
K_2O	2.31	4.81	5.66	3.65	4.06	2.37
H_2O	0.20	0.30	0.32	0.25	.....	0.55
Cl	....	....	....	....	0.54	...
F	....	....	....	....	0.08	....
ZrO_2	....	....	....	....	0.07	....
Total	99.67	99.71	99.83	100.17	99.75	99.63

I. Granite. Quarry granite known as the Wausau red granite. Consists mainly of albite, orthoclase, and quartz.

II. Amphibole granite (5298).[1] Consists mainly of microperthite, quartz, and an amphibole rich in ferric oxide, and alumina.

III. Hedenbergite-quartz syenite (5917). Consists mainly of microperthite, quartz, hedenbergite, arfvedsonite, lepidomelane, and fayalite.

IV. Amphibole syenite (6011). Consists mainly of orthoclase and bluish-green amphibole, and some magnetite, mica, fluorite, and zircon.

V. Sodalite-nepheline syenite (6426). Consists mainly of anorthoclase, nepheline, sodalite, and hedenbergite, with some fluorite.

VI. Nepheline syenite (5829). Consists mainly of nepheline, orthoclase, hedenbergite, and some fayalite.

It should be understood that not all the phases of rock represented in this alkali-rich series is indicated in the above table. Nor is the range in content of silica supposed to be outlined. Ægirite is a common constituent of many of the rocks, but analyses of the ægirite-bearing phases have not been made. Those who have studied the alkali-rich magmas can best appreciate the amount of work necessary, and the complexity of the problem met with, in describing these interesting rocks from the mineralogical standpoint. Some of the prevailing amphiboles, pyroxenes, and micas, as well as other minerals, have been separated from the rocks and analyzed, and hence where varietal names are used such use is based upon knowledge of the chemical composition. The object of the present paper is merely to describe the general character, occurrence, and signification of the fayalite found in various phases of the series, rather than a complete description of these rocks as a whole.

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[1] The numbers refer to specimens in the Wisconsin Survey collection.

The nature of the chemical and mineral composition of the series will be briefly referred to again. In the meantime it may be of interest to show how the true character of the fayalite was determined. Under the microscope it appears in ordinary light as a honey-yellow mineral, and under crossed nicols it has bright polarizing colors, resembling olivine. The minerals associated with it, however, such as an abundance of quartz, orthoclase, and albite, were not the ones usually found with olivine. The composition of the rock, with its very small amount of magnesia and the alteration product of the mineral wholly to iron oxide, free from serpentine, led to the idea that it might be fayalite.

A rough separation of the mineral was made by means of crushing the quartz syenite (like III) bearing considerable of the unknown mineral, and passing the finely crushed material through a Retgers solution of nitrate of thallium and nitrate of silver. A considerable amount of the heaviest material of the rock, which contained, besides the fayalite, some feldspar and pyroxene, was analyzed to see if any appreciable amount of magnesia was present, and to see if the theory that the yellow mineral was fayalite was probably correct.

The material was analyzed by Dr. Victor Lehner, and is seen to have been largely iron and silica, and almost entirely free from magnesia, as follows:

SiO_2	32 10%
Al_2O_3	3.54
Fe_2O_3	19.86
FeO	37.56
MgO	0.07
CaO	0.57
P_2O_5	none
MnO	trace
TiO_2	none
Undetermined	6.30
	100.00

After this rough test, a careful separation of the yellow mineral was made. With the Retgers solution the heavy minerals of the crushed rock were separated. It was impossible to separate with the Retger's solution the fayalite from the iron oxide, as the two were so intimately mixed by alteration and intergrowth. The iron oxide, which was strongly magnetic, was very largely removed by means of a magnet, and finally sorting out the honey-yellow fayalite from the magnetic iron oxide by hand had to be resorted to. After considerable work, 0.3610 grams of the nearly pure fayalite was separated, which was analyzed by Dr. Victor Lehner, and found to be as follows:

SiO_2	33.77%
Fe_2O_3	0.23
FeO	62.09
Undetermined	3.91
	100.00

The materials associated with the fayalite, and necessarily included in the analysis, were small particles of feldspar, quartz, pyroxene, and amphibole. The undetermined portion in this second analysis, 3.91 per cent., as indicated by comparison with the first rough analysis, is very probably mainly alumina and the alkalies which may be assumed to be combined with perhaps 4 or 5 per cent. of silica to form the associated silicate minerals. An additional source of silica, probably 1 or 2 per cent., was due to small included fragments of quartz. After deducting, therefore, an amount of silica—6 or 7 per cent.—present in mineral other than fayalite, it will be seen that the ferrous oxide and silica occur in approximately the proportions found in fayalite.

Under the microscope the fayalite has the appearance of this mineral as usually described. In ordinary light it has a light stone color, with yellowish-green or honey-yellow tints. It is distinctly pleochroic, the green tinge changing from a light to a darker shade. The double refraction is strong, probably stronger than for olivine. It apparently has two fairly well-defined planes of cleavage, as illustrated in Fig. 1, which are probably parallel to the pinnacoids, 001, and 010.

The fayalite occurs in the quartz-syenite, having a silica content of 61.18 per cent., and to a very small extent in the amphibole granite, bearing 67.99 per cent. silica. In phases of the quartz syenite it probably constitutes from 1 to 5 per cent. of the rock, and was noted in many thin sections of this variety from widely different parts of the district. In the rocks bearing quartz it is associated with the feldspars, orthoclase, albite, and microperthite; with the calcium-iron-amphibole, arfvedsonite; with the calcium-iron-pyroxene, hedenbergite; and with iron mica containing large amounts of potassium. In phases of the non-quartzose and nepheline-bearing rocks of the series the fayalite also contributes a fraction of 1 per cent. to as much as 5 per cent. of the rock. In some of the nepheline-rich rocks the fayalite is the only dark-colored mineral noted in the thin sections. In these rocks the fayalite occurs with orthoclase and microperthite, nepheline, sodalite, the soda amphiboles of the riebeckite, and crocidolite type, and the calcium-iron pyroxene, hedenbergite, and the potash-iron mica lepidomelane.

The various rocks in which the fayalite occurs is thus seen to have a considerable range in certain chemical constituents, such as silica, alumina, and the alkalies, and also in mineral composition. The area over which these rocks are distributed is quite extensive. The amphibole granite and quartz syenite cover several hundred square miles, and the nepheline-bearing and related basic rocks, from fifteen to twenty square miles.

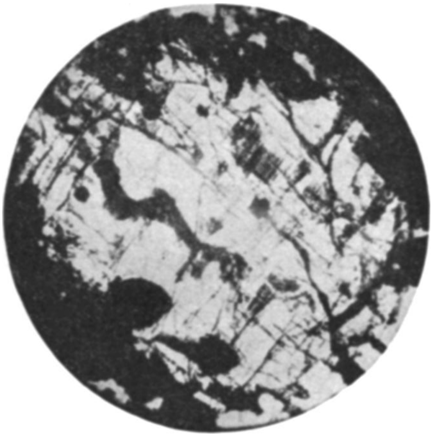

FIG. 1.—Photomicrograph of fayalite in nepheline syenite; ×60. The fayalite, light-colored, is surrounded on nearly all sides by a black border of magnetic iron oxide. Portions of it are in contact with feldspar and hedenbergite. The greatest length of the fayalite in this section is along the *c* axis, parallel to which is indistinct parting or cleavage. The areas within the fayalite are colored dark by photography, and in reality are yellowish-brown and bluish mineral inclusions. The yellowish-brown inclusions are in irregular areas, and are probably yellowish hydroxide of iron, göthite, formed by alteration of the fayalite. The bluish inclusions are finely striated crystals of a bluish amphibole.

The fayalite, in the various phases of rock in which it occurs, has the associations and relations of a normal, original constituent of the rock. It does not occur in veins, segregations, or cavities, but as a common constituent distributed through the rock, like the quartz, feldspar, nepheline, and other common rock-forming minerals with which it is associated.

Like the other abundant minerals associated with it, it does not occur in idiomorphic crystals, but assumes shapes in its development due to the mutual interference of surrounding minerals. Where present with an abundance of dark-colored silicates, it is usually in direct contact with them, but in quartz syenite it occurs in direct contact with quartz, and in certain phases of the nepheline syenite it is entirely surrounded by nepheline, or nepheline and feldspar.

The fayalite has not been observed to occcur with the alkali-iron pyroxene, ægirite, which is a common constituent of several phases of the nepheline-bearing rocks. While it may be stated with certainty that these two iron-rich minerals do not occur in the same thin sections of rock examined—and this includes a considerable number—with this special relation in mind, yet a final conclusion upon this point, it is believed, should be held in abeyance.

The pyroxene, ægirite, it will be recalled, contains a high percentage of ferric oxide and but a small proportion of ferrous oxide. On the other hand, the fayalite contains ferrous oxide only, and the pyroxenes, amphiboles, and micas abundantly associated with the fayalite, as shown by the analyses, contain a marked excess of ferrous oxide over ferric oxide.

It may be, therefore, that in those magmas, or portions of magmas, very poor in magnesia, which contain a large excess of ferrous oxide over ferric oxide, the chemical conditions for the development of fayalite exists, and in those containing an abundance of ferric oxide the conditions for the development of ægirite are present and that necessarily these two minerals will not be expressed in the same phase of rock. A deficiency of oxygen as well as of magnesia may therefore be necessary for the development of fayalite.

Fluorite is a persistent, though not an abundant, constituent of the various phases of this series. The fluorite is colorless, has low birefringence and perfect octahedral cleavage, and on account of its extremely low index of refraction, produces the apparent anomalous appearance of having a very high index of refraction. The occurrence of fluorite in the various members of this series is but another expression, in addition to that of the prevalence of the fayalite, of the probable common magmatic source of the various phases of rocks here referred to as belonging to the same series.

The idea has prevailed, to some extent at least, that fayalite, on account of its extremely basic character and its association with quartz in certain rocks, and with spherulites and lithophysae, probably had only an aqueo-igneous origin in rocks rather than ordinary igneous origin. In this connection it may be well to call attention to the various occurrences of fayalite previously noted.

It has often been observed in crystalline slags. The first natural occurrence of fayalite observed[1] was in 1839 in nodules in volcanic rocks on the island of Fayal (whence the name is derived), one of the islands of the Azores. In the Mourne Mountains of Ireland it occurs,[2] filling drusy cavities in granite. Professor J. P. Iddings,[3] has described its occurrence with tridymite in spherulites and lithophysae in the obsidian of Obsidian Cliff, Yellowstone National Park; and Iddings and Penfield[4] have described its occurrence in the recent obsidian flows of the Lipari Islands. It also occurs in large crystals, apparently in "vugs," in a soda granite at Cheyenne Mountain, Colorado,[5] and in a pegmatite dike in hornblende granite at Rockport, Mass.[6] In the latter place, as described by Penfield and Forbes, it occurs as a lenticular shell of varying thickness, twelve to sixteen inches in diameter, filled on the inside with loose earthy material and enveloped by a layer of magnetite one inch thick. It is a fact worthy of note that this Rockport granite is a phase of the alkali-rich rock of Essex County.[7]

It is also found in cavities in the lava of Vesuvius erupted in 1631, occurring with sodalite and orthoclase. Lacroix has also noted the occurrence of fayalite in the trachyte lava of Mont Doré. In all these instances, with the possible exception of the last mentioned, it will be noted that the fayalite occurs either in cavities, veins, or segregations, and on this account it has been thought that it must necessarily be a product of aqueo-igneous origin.

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[1] *Poggendorf's Annalen*, Vol. LI, p. 160.

[2] Delesse, *Bulletins de la Société géologique de France*, Vol. X (1853), p. 571.

[3] J. P. Iddings, *Seventh Annual Report*, U. S. Geological Survey (1885), pp. 270, 279.

[4] J. P. Iddings and S. L. Penfield, *American Journal of Science*, Vol. XL (1890), p. 75.

[5] W. E. Hidden and J. B. Macintosh, *ibid.*, Vol. XLI (1891), p. 439, and Vol. XXIX (1885), p. 250.

[6] S. L. Penfield and E. H. Forbes, *ibid.*, Vol. LI (1890), p. 129.

[7] H. S. Washington, Journal of Geology, Vol. VII (1899), p. 466.

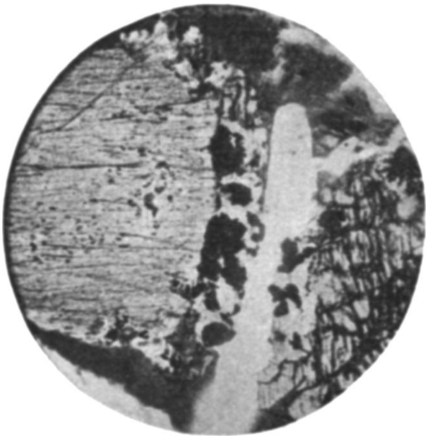

FIG. 2.—Photomicrograph of quartz-syenite; ×60. The crystals shown are fayalite, much fractured, on the right, hedenbergite on the left, both surrounded in part by bluish-green arfvedsonite. The black mineral is magnetite, and the colorless crystal is apatite.

It may be well, therefore, again to call attention to, and emphasize, the fact that not only does the fayalite occur as a persistent, and in places a fairly abundant, constituent of these various rocks described from central Wisconsin, but that it occurs here as a rock constituent under perfectly normal conditions.

The presence of fayalite as an essential constituent of a number of phases of this series would seem to indicate that, mineralogically and chemically, these phases are unique. And not only are the fayalite-bearing phases unusual, but also the other phases of the series, since they contain no magnesia-bearing minerals, and contain, besides the quartz, feldspar, and feldspathoids, only calcic-iron alumino silicates or alkali-iron alumino silicates, or combinations of them. It is a well-known fact, of course, that all the alkali-rich rocks, such as those associated with nepheline-bearing rocks, contain much less magnesia than lime, and that not only is the proportion of magnesia to lime in these alkali rocks small as compared with the proportion in the usual basic rocks, but that it is also much smaller than occurs in average igneous rocks.

In comparison with other somewhat similar and well-known alkali-rich rocks, such as the nepheline-bearing and associated rocks of the Christiania region of southern Norway, described by Brögger,°

° W. C. BRÖGGER, *Zeitschrift für Krystallographie und Mineralogie*, Vol. XVI (1890).

it may be stated that the latter differ radically from the alkali rocks of Wisconsin in their much higher content of magnesia. In Brögger's series there is, on the average, five or six times as much magnesia as in these, otherwise similar, Wisconsin rocks. The nepheline syenites and quartz syenites of Arkansas, described by J. Francis Williams,[1] are more like these Wisconsin rocks, but the Arkansas rocks, otherwise similar, have much more magnesia than those here described. The nepheline-bearing and associated rocks of Essex County,[2] Mass., are generally comparatively high in magnesia and are closely related to gabbro and diorite.

When the mineralogical composition of these various alkali rocks, from different parts of the world, is compared, a much more striking dissimilarity is to be noted. The difference, of course, does not lie in the nature of the quartz, feldspar, nepheline, and sodalite, but with the dark-colored silicates; and since the former constitute much the larger portion of the rock, the difference is necessarily accentuated in the less abundant iron silicates. In these Wisconsin rocks, therefore, the low content of magnesia finds expression in the development of fayalite, and of pyroxenes, amphiboles, and micas comparatively low or free from magnesia. Whether or not fayalite or other magnesia-free silicate develops in the magma probably depends also, as already stated, upon the oxide condition of the iron. A deficiency of oxygen in the magma, as well as of magnesia, therefore, may be the controlling factors in the development of fayalite; and in those portions of the magma where oxygen was more abundant the more complex ferric-oxide-bearing silicates, such as ægirite, were formed.

In comparison with other somewhat similar, alkali-rich rock series, such as the syenite of southern Norway, Arkansas, and Essex County, Mass., it may be stated that fayalite has not been observed in any of them. Furthermore, the pyroxenes present in these rocks are generally the magnesia-rich varieties, such as augite or diopside, which tend to grade to ægirite through augite-ægirite and diopside-ægirite.

The alteration of the fayalite in some instances is quite extensive, the process of alteration consisting merely in the breaking up of this

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[1] J. F. WILLIAMS, *Arkansas Geological Survey*, Vol. II (1891).

[2] H. S. WASHINGTON, JOURNAL OF GEOLOGY, Vol. VII (1899), p. 463.

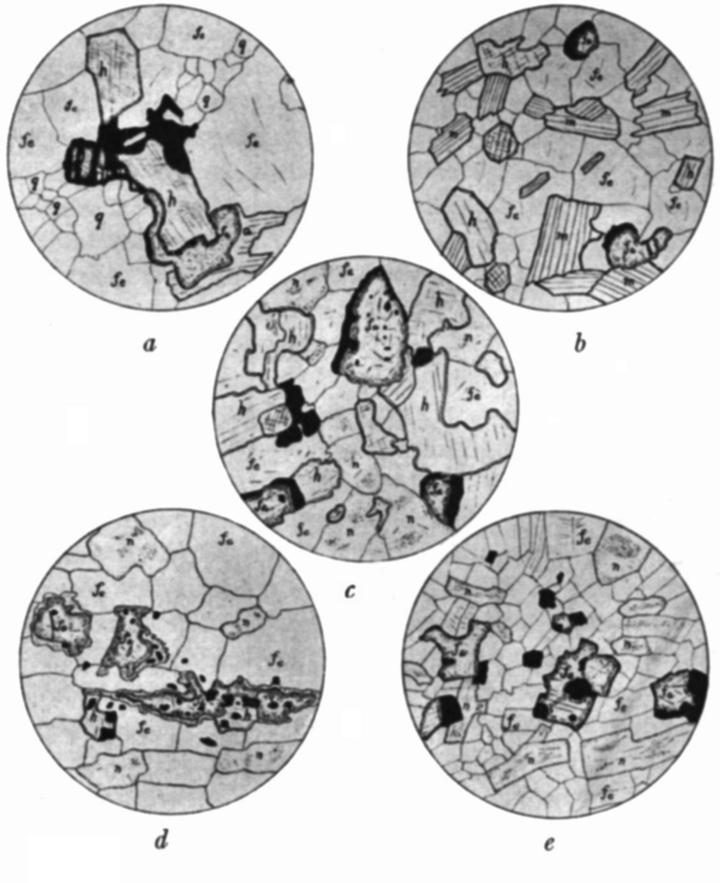

FIG. 3.—*a*. Hedenbergite-quartz-syenite (6639); ×20. The minerals shown are: alkali-feldspar (*fe*), quartz (*q*), fayalite (*fa*), hedenbergite (*h*), arfvedsonite (*a*), and magnetite, the black mineral. There is also present a small amount of fluorite and apatite.

b. Hedenbergite-mica-syenite (6597); ×20. The minerals shown are: alkali-feldspar (*fe*), brown mica (*m*), hedenbergite (*h*), fayalite (*fa*), and magnetite. A small amount of fluorite and apatite is also present.

c. Hedenbergite-nepheline-syenite (6600); ×20. The minerals shown are: alkali-feldspar (*fe*), nepheline (*n*), hedenbergite (*h*), fayalite (*fa*), and magnetite.

d. Fayalite-nepheline-syenite (5275); ×20. The minerals shown are: alkali-feldspar (*fe*), nepheline (*n*), hedenbergite (*h*), fayalite (*fa*), and magnetite.

e. Fayalite-nepheline-syenite (5275); ×20. The minerals shown are: alkali-feldspar (*fe*), nepheline (*n*), fayalite (*fa*), and magnetite.

ferrous silicate mineral into the oxide of iron and oxide of silica, the silica being carried away in solution, probably as hydroxide of silica, and the oxide of iron, which is apparently always magnetic, left as residual material. Quartz as an undoubted residual product of the alteration was not observed in any case. The alteration of the fayalite to magnetite, as indicated in the photomicrograph, takes place about the borders of the crystals, and along the fractures and cleavage.

Not all the iron oxide associated with the fayalite, however, is of secondary origin. There can be little doubt that some of the iron oxide occurring as rims surrounding the fayalite, as well as that occurring as inclusions within the fayalite, is of primary origin. The distribution of the iron oxide, probably mainly magnetite, is such as to indicate that most of it occurring in the rocks is an original separation from the magma, for it is by no means entirely confined to the vicinity of the fayalite, or of the other dark-colored constituents, but often appears to be entirely independent of them. (See Figs. 1–3.) Rims of hedenbergite also surround the fayalite (Fig. 3, *d*), and sometimes the reverse is true and fayalite and iron oxide nearly completely surround hedenbergite (Fig. 3, *a*). Furthermore, these associations are just as abundant in perfectly fresh rocks, as illustrated in phases from a well taken fifty or sixty feet from the surface, as in specimens collected from the rapids of the Wisconsin River at Wausau, and elsewhere, immediately beneath the soil.

While much of the fayalite appeared to show more or less alteration, still in most cases the alteration was never complete, at least in crystals of the ordinary, or average, size, even when the fayalite-bearing rock was immediately associated with the soil, or running water. Attention has already been called to the alteration of the large nodules of fayalite in pegmatite, sixty feet below the surface, at Rockport, Mass., where the magnetite was observed as forming a shell about the fayalite. In all other cases noted in literature, the alteration of fayalite has been quite generally observed as being to magnetic material, and in this regard it is quite similar to the alteration of olivine, in which case the secondary products are usually serpentine and magnetite.

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